SOLE INVENTOR

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APPLICATION FOR
UNITED STATES LETTERS PATENT

SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

Be it known that I, Mats A. Brenner, a citizen of Sweden, residing at 4275 Deerwood Lane, in the County of Hennepin and State of Minnesota have invented a new and useful APPARATUS FOR NAVIGATION SATELLITE SIGNAL QUALITY MONITORING, of which the following is a specification.

APPARATUS FOR NAVIGATION SATELLITE
SIGNAL QUALITY MONITORING

Technical Field of the Invention

The present invention relates generally to satellite based positioning systems such as the Global Positioning System (GPS) and more particularly to the monitoring of the quality of the signals transmitted by satellites in a satellite based positioning system.

Background of the Invention and Prior Art

A satellite based positioning system is used to determine a position of a receiver and typically includes satellite control facilities, a plurality of satellites, the receiver, and one or more local or regional ground stations. Each of the satellites transmits a signal that contains a code and certain prescribed information useful to the receiver in determining its position. The receiver synchronizes itself to the codes of at least four satellites and uses the information in the signals from these satellites in order to perform a triangulation like procedure so as to determine its coordinates and time offset with respect to a reference, such as the center of the Earth and the GPS standard time.

The receiver is not constrained to a specific location and, therefore, represents a variable position. Indeed, the purpose of the satellite based positioning system is to make it possible for the receiver to determine its position regardless of the location of the receiver. On the other hand, the local or regional ground station is in a fixed location and is used to monitor the signals transmitted by the satellites. The signals transmitted by the satellites can be adversely affected, for example, by atmospheric conditions which can lead to improper position determinations by the receiver. The ground station, therefore, notifies the receiver of any necessary signal corrections to allow the receiver to make more accurate position calculations. This arrangement is referred to as differential positioning.

The ground station of the present invention also monitors the signals transmitted by the satellites in order to detect faults within the satellites. For GPS, these faults are specified by the FAA who imposes stringent requirements to protect users against positioning system signal faults. A set of test waveforms has been chosen by the FAA to represent at least some of the more egregious faults. These waveforms

are used for certification testing of the ground station equipment.

The prior art determines faults by comparing conventional code tracking discriminators at different correlator spacings. As shown in Figure 1, a correlation curve is established by correlating the code received from a satellite with a suite of code references which are time shifted replicas of the code transmitted by that satellite. For example, seven correlation measurements may be calculated as shown in Figure 1. The in-phase measurement IP represents the amount of correlation between the received code and a reference code that has a zero time shift with respect to the received code (this measurement is referred to as punctual). The in-phase measurement IE_1 represents the amount of correlation between the received code and a reference code that has a first predetermined time shift so that it is early with respect to the received code. The in-phase measurement IL_1 represents the amount of correlation between the received code and a reference code that has a second predetermined time shift so that it is late with respect to the received code. Similarly, the in-phase measurement IE_2 is derived using a third predetermined time shift, the in-phase measurement IL_2 is derived using

a fourth predetermined time shift, the in-phase measurement IE_3 is derived using a fifth predetermined time shift, and the in-phase measurement IL_3 is derived using a sixth predetermined time shift. The magnitude of the first predetermined time shift may be equal to the magnitude of the second predetermined time shift, the magnitude of the third predetermined time shift may be equal to the magnitude of the fourth predetermined time shift, and the magnitude of the fifth predetermined time shift may be equal to the magnitude of the sixth predetermined time shift. It is assumed that all measurements are normalized such that the measured correlation is a function of the time shifts only and not the absolute power of the received satellite signal.

First, second, and third discriminators are then formed according to the following equations:

$$d_1 = (IL_1 - IE_1)IP$$

$$d_2 = (IL_2 - IE_2)IP$$

$$d_3 = (IL_3 - IE_3)IP$$

These discriminators are thereafter compared to each other through the formation of quantities $d_{1,2}$, $d_{1,3}$, and $d_{2,3}$ according to the following equations:

$$d_{1,2} = |d_1 - d_2|$$

$$d_{1,3} = |d_1 - d_3|$$

$$d_{2,3} = |d_2 - d_3|$$

The quantities $d_{1,2}$, $d_{1,3}$, and $d_{2,3}$ are compared to corresponding thresholds $D_{1,2}$, $D_{1,3}$, and $D_{2,3}$ such that, if the first discriminator $d_{1,2}$ exceeds $D_{1,2}$, if the second discriminator $d_{1,3}$ exceeds $D_{1,3}$, or if the third discriminator $d_{2,3}$ exceeds $D_{2,3}$, a fault is assumed to exist. During normal operation of the global positioning system, this test is performed on the signals received from each of the satellites. During certification, a test is to be performed using each of the test waveforms chosen by the FAA in order to prove that fault detection occurs.

At least one of the problems with this method is that it is requires six correlators in order to determine the three quantities $d_{1,2}$, $d_{1,3}$, and $d_{2,3}$ which is

too much hardware for the amount of useful data being provided.

It is also known for ground stations to determine faults by scanning the whole correlation peak (i.e., the portion of the correlation curve around the punctual in-phase measurement IP) in order to determine whether the peak varies from some prescribed norm by a predetermined amount. However, this fault detection arrangement requires a substantial amount of computing power and it lacks accuracy.

A third method in the prior art uses the following ratios between the measurements IE3, IE2, IE1, IL1, IL2, and IL3:

$$r_{E3,E2} = \frac{IE3}{IE2}$$

$$r_{E3,E1} = \frac{IE3}{IE1}$$

$$r_{E3,L1} = \frac{IE3}{IL1}$$

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Each of these ratios is compared to a corresponding predetermined value.

The present invention is directed to an arrangement which overcomes one or more problems of the prior art.

Summary of the Invention

In accordance with one aspect of the present invention, an apparatus for the detection of positioning system satellite signal faults comprises a correlator and a fault detector. The correlator determines a plurality of correlation measurements at points along a correlation curve, and each correlation measurement is based upon a correlation between a received satellite signal and a reference. The fault detector determines differences between the correlation measurements along the correlation curve and detects a fault from the differences.

In accordance with another aspect of the present invention, a method of detecting faults affecting a signal transmitted by a positioning system satellite comprises: correlating the transmitted signal with a first reference in order to determine a first correlation measurement at a first point along a correlation curve;

correlating the transmitted signal with a second reference in order to determine a second correlation measurement at a second point along the correlation curve; correlating the transmitted signal with a third reference in order to determine a third correlation measurement at a third point along the correlation curve; determining a first difference from the first and second correlation measurements; determining a second difference from the second and third correlation measurements; directly comparing the first difference to a first threshold; directly comparing the second difference to a second threshold; and, detecting a fault in the satellite based upon the comparisons of the first and second differences to the first and second thresholds.

In accordance with still another aspect of the present invention, a method of detecting faults affecting a signal transmitted by a positioning system satellite comprises: correlating the transmitted signal with references in order to determine a plurality of correlation measurements at corresponding points along a correlation curve; determining a single value from n pairs of the correlation measurements, wherein $n > 2$; comparing the single value to a threshold; and,

detecting a fault in the satellite based upon the comparison.

Brief Description of the Drawings

These and other features and advantages will become more apparent from a detailed consideration of the invention when taken in conjunction with the drawings in which:

Figure 1 is a waveform showing a correlation diagram useful in explaining prior art fault detection as implemented in a ground station in a global positioning system;

Figure 2 is a schematic diagram of a portion of a ground station receiver pertinent to the present invention; and,

Figure 3 is a waveform showing a correlation diagram useful in explaining fault detection as implemented by a ground station in a global positioning system in accordance with the present invention.

Detailed Description

A portion of a ground station 10 pertinent to the present invention is shown in Figure 2. The ground station has correlators 12-E_m, . . . , 12-E_3, 12-E_2, 12-E_1,

12-P, $12\text{-}L_1$, $12\text{-}L_2$, $12\text{-}L_3$, . . ., $12\text{-}L_n$, where n + m is greater than two, and where n is the number of late correlation measurements and m is the number of early correlation measurements to be used in determining a fault. The correlator 12-P correlates the usual code in the received signal with a reference 14-P to produce a punctual correlation output IP, the correlator $12\text{-}L_1$, correlates the code in the received signal with a reference $14\text{-}L_1$ to produce a late correlation output IL_1, the correlator $12\text{-}L_2$ correlates the code in the received signal with a reference $14\text{-}L_2$ to produce a late correlation output IL_2, the correlator $12\text{-}L_3$ correlates the code in the received signal with a reference $14\text{-}L_3$ to produce a late correlation output IL_3, . . ., and the correlator $12\text{-}L_n$ correlates the code in the received signal with a reference $14\text{-}L_n$ to produce a late correlation output IL_n.

In addition, a correlator $12\text{-}E_1$ correlates the code in the received signal with a reference $14\text{-}E_1$ to produce an early correlation output IE_1, a correlator 12-E_2 correlates the code in the received signal with a reference $14\text{-}E_2$ to produce an early correlation output IE_2, a correlator $12\text{-}E_3$ correlates the code in the received signal with a reference $14\text{-}E_3$ to produce an

early correlation output IE_3, . . ., and a correlator 12-E_m correlates the code in the received signal with a reference 14-E_m to produce an early correlation output IE_m.

Sub A1

~~The ground station 10 has a processor 16 which uses the punctual and late correlation outputs IP, IL_1, IL_2, IL_3, . . ., IL_n as disclosed hereinafter in order to determined whether a fault exists. Alternatively or additionally, the processor 16 can use the early correlation outputs IE_1, IE_2, IE_3, . . ., IE_m as disclosed hereinafter in order to determined whether a fault exists.~~

In order to generate the punctual correlation output IP, the processor 16 shifts the reference 14-P, which may be a replica of the code contained in the received signal, until an optimum correlation is obtained. The processor 16 then controls the reference 14-L_1 so that the reference 14-L_1 is a replica of the reference 14-P and so that the reference 14-L_1 is time shifted with respect to the reference 14-P by a first predetermined amount of time. Accordingly, the correlator 12-L_1 produces the late correlation output IL_1. The processor 16 also controls the reference 14-L_2 so that the reference 14-L_2 is a replica of the reference

14-P and so that the reference $14\text{-}L_2$ is time shifted with respect to the reference 14-P by a second predetermined amount of time, where the second predetermined amount of time is greater than the first predetermined amount of time. Accordingly, the correlator $12\text{-}L_2$ produces the late correlation output IL_2. Similarly, the processor 16 controls the reference $14\text{-}L_3$ so that the reference $14\text{-}L_3$ is a replica of the reference 14-P and so that the reference $14\text{-}L_3$ is time shifted with respect to the reference 14-P by a third predetermined amount of time, where the third predetermined amount of time is greater than the first and second predetermined amounts of time. Accordingly, the correlator $12\text{-}L_3$ produces the late correlation output IL_3. The remaining late correlation outputs up to IL_n are generated in a like manner. The first, second, third, etc. predetermined amounts of time are all chosen so that the late correlation outputs IL_1 through IL_n are all on the downward or late slope of the correlation curve as shown in Figure 3.

Additionally or alternatively, the correlators $12\text{-}E_1$, $12\text{-}E_2$, $12\text{-}E_3$, . . ., $12\text{-}E_m$ may be positioned so as to generate the early correlation outputs IE_1, IE_2, IE_3, . . ., IE_m. Also, quadrature phase correlation outputs QE_m, . . ., QE_1, QP, QL_1, . . ., QL_n may be generated by

correlating the code in the received signal to a time shifted quadrature form of the reference 14-P. In accordance with this latter alternative, each measurement used to generate a fault indication may be formed as an RMS (Root Mean Square) value of the corresponding in phase and quadrature phase measurements.

The set $IE_m, \ldots, IE_3, IE_2, IE_1, IP, IL_1, IL_2, IL_3, \ldots, IL_n$ may be denoted as $I_m, \ldots, I_{-3}, I_{-2}, I_{-1}, I_0, I_1, I_2, I_3, \ldots, I_n$ and the following corresponding set of RMS values

$$\sqrt{IE_m^2 + QE_m^2}, \ldots, \sqrt{IE_1^2 + QE_1^2}, \sqrt{IP^2 + QP^2}, \ldots, \sqrt{IL_n^2 + QL_n^2}$$

may be denoted as $R_m, \ldots, R_{-3}, R_{-2}, R_{-1}, R_0, R_1, R_2, R_3, \ldots, R_n$.

If early as well as late correlation outputs are to be used for fault detection, the processor 16 processes the early correlation outputs IE_m through IE_1, the punctual correlation output IP, and/or the late correlation outputs IL_1 through IL_n so as to derive one or more measured differences $d_{i,j}$. These measured differences $d_{i,j}$ are generated in accordance with the following equations:

$$d_{i,j} = I_i - I_j \qquad (1)$$

or

$$d_{i,j} = R_i - R_j \qquad (2)$$

where i = -m, . . ., n and j = -m, . . ., n, and where the negative sign indicates measurements on the early slope and the positive sign indicates measurements on the late slope of the correlation curve.

At this point, it is possible to subtract the expected difference from all or a subset of these measured differences $d_{i,j}$ and to compare the resulting difference deviations to corresponding thresholds in order to determine the existence of a fault. For example, assuming that all of these difference deviations are used, then these difference deviations may be compared to corresponding thresholds in accordance with the following equation:

$$|d_{i,j} - Ed_{i,j}| > D_{i,j} \qquad (3)$$

where $Ed_{i,j}$ is the difference that is expected for each corresponding measured difference $d_{i,j}$ when there is no fault.

In some cases, the measured differences $d_{i,j}$ may be affected by thermal and multipath noise which could lead to false detection of faults, depending upon the sensitivity of the fault detection apparatus, i.e., the magnitudes of the thresholds $D_{i,j}$. Accordingly, in these cases, a fault could be detected when no fault is in fact present, or a fault which is present might not be detected at all.

The thermal noise content in $d_{i,j}$ can be determined as a function of the delay $h_{i,j}$ between the reference codes 14-E_m, . . ., 14-E_3, 14-E_2, 14-E_1, 14-P, 14-L_1, 14-L_2, 14-L_3, . . ., 14-L_n. The delay $h_{i,j}$ is the delay between the two references that are correlated with the received signal to produce I_i and I_j. Typically, $h_{i,j}$ = 0.025 to 0.05 chip, but may vary from this range. The thermal noise th1 in $d_{i,j}$ depends on the signal to noise ratio and the standard deviation (1-sigma) of th1 and is given by the following equation:

$$\sigma_{th1}(i,j) = 293\sqrt{\frac{h_{i,j}B}{S/No}} \qquad (4)$$

where B is the two-sided bandwidth of the noise. In addition, there is another contribution, th2, to the thermal noise due to the variation of the punctual reference (i.e., the reference 14-P). Accordingly, the total thermal noise is th = th1 + th2. The multipath noise mp depends on the antenna gain pattern and its overbounding 1-sigma $\sigma_{mp}(i,j)(\dot{e})$ is expressed as a function of satellite elevation $\dot{e}$. The statistical properties of th and mp are usually identified at installation of the ground station and the statistical information is parameterized and are thereafter stored in memory.

One way to minimize any adverse effects of thermal and multipath noise is to make a plurality of measurements for each of the measured differences $d_{i,j}$ that are used in the detection of faults. Then, the measurements for each of the measured differences $d_{i,j}$ may be averaged or filtered. Because the thermal noise and some of the multipath noise are not particularly correlated from one measurement to the next, averaging will tend to reduce the effects of thermal and multipath noise.

As an example, let it be assumed that the punctual correlation output IP and the late correlation

outputs IL_1 and IL_2 are used to detect faults. Accordingly, the following measured differences are determined: $d_{0,1} = IP - IL_1$; $d_{0,2} = IP - IL_2$; and, $d_{1,2} = IL_1 - IL_2$. In order to reduce the effects of thermal and multipath noise, however, plural calculations of the measured difference $d_{0,1}$ are made based upon plural correlation measurements resulting in plural punctual correlation outputs IP and plural late correlation outputs IL_1. All such calculations of the measured difference $d_{0,1}$ are then averaged. Similarly, plural calculations of the measured difference $d_{0,2}$ are made based upon the plural correlation measurements resulting in plural punctual correlation outputs IP and plural late correlation outputs IL_2. As before, all such calculations of the measured difference $d_{0,2}$ are averaged. Likewise, plural calculations of the measured difference $d_{1,2}$ are made based upon the plural correlation measurements resulting in the plural late correlation outputs IL_1 and plural late correlation outputs IL_2. Again, all such calculations of the measured difference $d_{1,2}$ are averaged. These averages may then be compared to their corresponding thresholds $D_{0,1}$, $D_{0,2}$, and $D_{1,2}$ in order to determine the existence of a fault.

Another way to reduce the effect of thermal and multipath noise is to suitably filter the measured differences $d_{i,j}$, or the punctual correlation output IP, the late correlation outputs IL_1 through IL_n, and the early correlation outputs IE_1 through IE_m, such as with a low pass filter.

Still another way to reduce the effect of thermal and multipath noise is by implementing the following procedure. In describing this procedure, it is useful to define a covariance matrix P in accordance with the following equation:

$$P = E[(\underline{d} - \underline{m})(\underline{d} - \underline{m})^T] \tag{5}$$

where the underlines indicate vectors, where E[A] is the statistical expectation of A, where the vector $\underline{m}$ is the mean value of the vector $\underline{d}$, and where the vector $\underline{d}$ is determined in accordance with the following equation:

$$\underline{d}^T = (d_1, d_2, d_3, d_4, \ldots, d_N) \tag{6}$$

where $d_k = I_k - I_{k-1} - Ed_k$ for $k = -m, \ldots, n-1$ or where $d_k = R_k - R_{k-1} - Ed_k$ for $k = -m, \ldots, n-1$ assuming N + 1 correlation measurements such as $I_m, \ldots, I_{-3}, I_{-2}, I_{-1}$,

I_0, I_1, I_2, I_3, . . ., I_n. An upper triangular matrix U and a diagonal matrix D are determined according to the following equation:

$$P = UDU^T \tag{7}$$

where P is the covariance matrix given by equation (6). With the covariance matrix P known from equation (6), the upper triangular matrix U and the diagonal matrix D can be determined, for example, by using Cholesky factorization. Thus, the following relationship may be defined in accordance with the following equation:

$$\underline{\tilde{d}} = U^{-1}(\underline{d} - \underline{m}) \tag{8}$$

Sub A2

where $\underline{\tilde{d}}$ is a vector representing the decorrelated deviations generating the vector $\underline{d}$. Equation (9) can be re-written according to the following equation:

$$\underline{d} = U\underline{\tilde{d}} + \underline{m} \tag{9}$$

Sub A3

Then, combining equations (6) and (10) produces the following equation:

$$P = E\,[U\,\underline{\tilde{d}}\,(U\,\underline{\tilde{d}})^T] = U\,E\,[\underline{\tilde{d}}\,(\underline{\tilde{d}})^T]\,U^T \tag{10}$$

Sub A4

By comparing equations (6) and (11), it can be seen that D is given by following equation:

$$D = E\,[\underline{\tilde{d}}\,(\underline{\tilde{d}})^T] \tag{11}$$

and that D, as defined above, is a diagonal matrix having the following format:

$$D = \begin{bmatrix} \tilde{\sigma} & 0 & 0 & \dots & 0 \\ 0 & \tilde{\sigma} & 0 & \dots & 0 \\ 0 & 0 & \tilde{\sigma} & \dots & 0 \\ . & . & . & . & . \\ . & . & . & . & . \\ 0 & 0 & 0 & \dots & \tilde{\sigma} \end{bmatrix} \tag{12}$$

Variances $\tilde{\sigma}_i^2$ are then determined from the diagonal matrix D. As can be seen from the above equations, the deviations in the vector $\underline{\tilde{d}}$ where i varies from 1 to N are uncorrelated and have the variances $\tilde{\sigma}_i^2$.

The final χ^2 value for determining a fault is obtained according to the following equation:

$$d[\chi^2] = \sum_{i=1}^{n} \frac{\tilde{d}_i^2}{\tilde{\sigma}_i^2} \tag{13}$$

A normalization to $\sigma = 1$ as required in the definition of χ^2 will be performed in equation (14). The value $d[\chi^2]$ is a single value which has reduced thermal and multipath noise, which represents information regarding a plurality of correlation measurements, and which may be compared to a threshold D in order to determine the existence of a fault.

Sub A5

Certain modifications of the present invention have been discussed above. Other modifications will occur to those practicing in the art of the present invention. For example, as described above, the χ^2 distribution is based on the assumption that all involved distributions are Gaussian. The distributions of d_k may deviate from this assumption and appropriate corrections to the formulas given here may be necessary.

Moreover, the present invention has been described above in connection with the detection of satellite signal faults such as those specified by the

FAA. These faults result in signal distortions detectable by use of the present invention. The present invention as embodied by the following claims can also be used to detect other signal distortions such as those arising from multipath and satellite code cross correlation effects.

Accordingly, the description of the present invention is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the best mode of carrying out the invention. The details may be varied substantially without departing from the spirit of the invention, and the exclusive use of all modifications which are within the scope of the appended claims is reserved.